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Breakup Morphology and Mechanisms of Liquid Atomization

Hui Zhao and Haifeng Liu

Abstract

Fuel atomization, the transformation of bulk liquid into sprays, is of importance in jet engines. In this chapter, we will introduce the latest research advances on breakup morphology and mechanism of liquid atomization. On primary atomization, based on the morphological difference, the twin-fluid atomization could be classified into different regimes. The influence of Kelvin-Helmholtz and Rayleigh-Taylor instability on breakup morphology and fragment size is great and nonmonotonic. On secondary atomization, Rayleigh-Taylor instability is considered as the main driving mechanism in different bag-breakup modes; for higher Weber number, it will be in concurrence with the shear instability. Based on ligament-mediated spray formation model, ligament breakup is found to be well represented by the gamma distributions. Atomization of complex fluids has special characteristics and mechanisms. There are also a lot of research advances recently in this field.

Keywords: atomization, sprays, breakup, drop, instability

1. Introduction

Transformation of bulk liquid fuel into sprays is of importance in many engines. Most fuels employed in engines are liquid that must be atomized before being injected into combustion zone. Atomization could produce a very high ratio of surface to mass in the liquid phase, thereby promoting rapid reaction and combustion. In addition, liquid atomization is also common in a wide array of applications, such as agriculture, coatings, gasification, water scrubber, pharmaceuticals, metal powder production, 3D printing, spray drying, fire suppression, and cooling.

Atomization quality can be described in terms of mean drop size and distribution. Important factors in atomization include the flow conditions, liquid properties, gas properties, atomizer (or nozzle, injector) dimensions, and environment conditions. So, there are many atomizer types in the industry and laboratory, such as pressure atomizers, air-blast atomizers, air-assist atomizers, rotary atomize, effervescent atomizers, electrostatic atomizers, ultrasonic atomizers, etc. Then, the key is to select the suitable atomizers for the given application, which can have a well performance in operating conditions.

Atomization process usually consists of the initial removal of liquid mass from the surface to form large liquid drops and the subsequent breakup of these drops into tiny droplets; the phenomena are, respectively, known as primary and

secondary atomization. Atomization has been quantitatively studied for more than a century. However, liquid atomization is a complicate, multiparameter two-phase flow process, which is not well understood. Many empirical theories and equations have been developed and used in atomization. So, there is still a lot of unknown work to be done [1–15].

2. Dimensionless number

The physical processes and fluid properties are important in atomization morphology and performance, and the mathematical and numerical analysis of atomization is very challenging, so a number of dimensionless numbers are used. First of all, the most important one is Weber number, which represents the ratio of disruptive hydrodynamic forces to the stabilizing surface tension force,

$$We = \frac{\rho_g (u_g - u_l)^2 D}{\sigma}, \quad (1)$$

where ρ_g is the gas density, u_g is the gas velocity, u_l is the liquid velocity, D is the characteristic size (in general, nozzle diameter in primary atomization and drop diameter in secondary atomization), and σ is the surface tension. Liquid viscosity will hinder deformation and dissipates energy supplied by aerodynamic forces. The viscosity effect is highly correlated with the Ohnesorge number,

$$Oh = \frac{\mu_l}{\sqrt{\rho_l D \sigma}}, \quad (2)$$

where μ_l is the liquid viscosity, and ρ_l is the liquid density. Other important dimensionless groups are gaseous Reynolds number

$$Re_g = \frac{\rho_g u_g D}{\mu_g}, \quad (3)$$

liquid Reynolds number

$$Re_l = \frac{\rho_l u_l D}{\mu_l}, \quad (4)$$

Mach number

$$Ma = u_g / c, \quad (5)$$

Strouhal number

$$St = \frac{fD}{u_l}, \quad (6)$$

the characteristic time [16]

$$T = \frac{tu_g}{D} \sqrt{\frac{\rho_g}{\rho_l}}, \quad (7)$$

gas-liquid momentum flux ratio

$$M = \frac{\rho_g u_g^2}{\rho_l u_l^2}, \quad (8)$$

momentum ratio

$$MR = \frac{\rho_g u_g^2 A_g}{\rho_l u_l^2 A_l} \quad (9)$$

and mass ratio

$$GLR = \frac{\rho_g u_g A_g}{\rho_l u_l A_l}. \quad (10)$$

Here μ_g is the gas viscosity, c is the speed of sound in the medium, f is the frequency, t is the real time, and A_g and A_l are the area of gas exit and liquid exit, respectively.

Complex fluid is usually a kind of complicated non-Newtonian fluid, which has more dimensionless groups on atomization. For example, in the Bingham model, the flow is characterized by the following constitutive equations,

$$\tau = \tau_0 + \eta\gamma \text{ and } \mu_l = \tau_0/\gamma + \eta, \quad (11)$$

where τ is the shear stress, τ_0 is the yield stress, η is the plastic viscosity, and γ is the shear rate. Hedstrom number is the useful nondimensional number, which depends only on material properties and geometrical parameters,

$$He = \frac{\tau_0 D^2 \rho}{\eta^2}. \quad (12)$$

The ratio of the yield stress to the stabilizing surface tension force is [17]

$$X = \tau_0 D / \sigma, \quad (13)$$

and the ratio of the aerodynamic force to the yield stress is [17]

$$Y = \rho_g u_g^2 / \tau_0. \quad (14)$$

For viscoelastic fluids, Weissenberg number compares the elastic forces to the viscous forces

$$Wi = N_1 / \tau \text{ or } Wi = t_R \gamma, \quad (15)$$

where N_1 is the first normal-stress difference, and t_R is the relaxation time. Another dimensionless number on the ratio of first normal stress difference to surface tension force could be defined as follows [18]

$$Z = \frac{N_1}{\sigma D}. \quad (16)$$

3. Primary atomization

Nozzle is generally used to produce spray. Fuel injection process plays a major role in many aspects of combustion performance. The influence of nozzle structure is remarkable on the atomization performance [19–22]. With the progress of technology

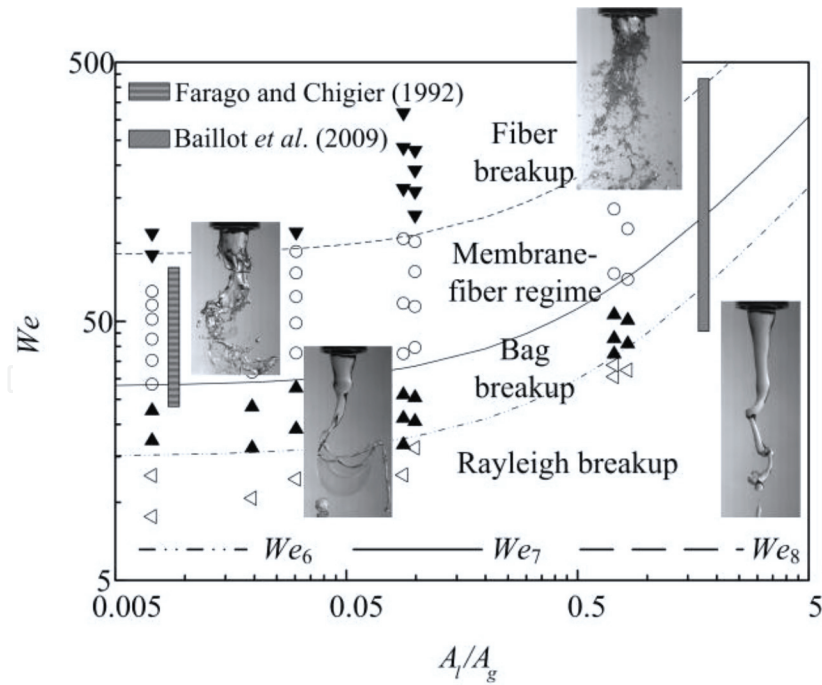


Figure 1.
Influence of A_g/A_l on atomization mode.

[23], it is found that the properties of breakup morphology and fragment distribution in different regimes are different [24–28]. Coaxial air-blast atomizers have many applications [29–31]. In order to obtain the desired results of atomization in the industrial scale, the suitable range of nozzle size and operating condition could be determined with the help of the regime map. There are two basic types on coaxial gas-liquid jets: (I) a cylindrical liquid jet surrounded by an annular gaseous stream and (II) an annular liquid sheet with an inner round gaseous stream [32–35].

In cylindrical liquid jet and annular gas jet, the common atomization modes are Rayleigh-type breakup (axisymmetric and non-axisymmetric), the membrane-type breakup (bag-type and membrane-fiber), fiber-type breakup, superpulsating breakup, atomization, and so on [36–42]. For the traditional classification, the

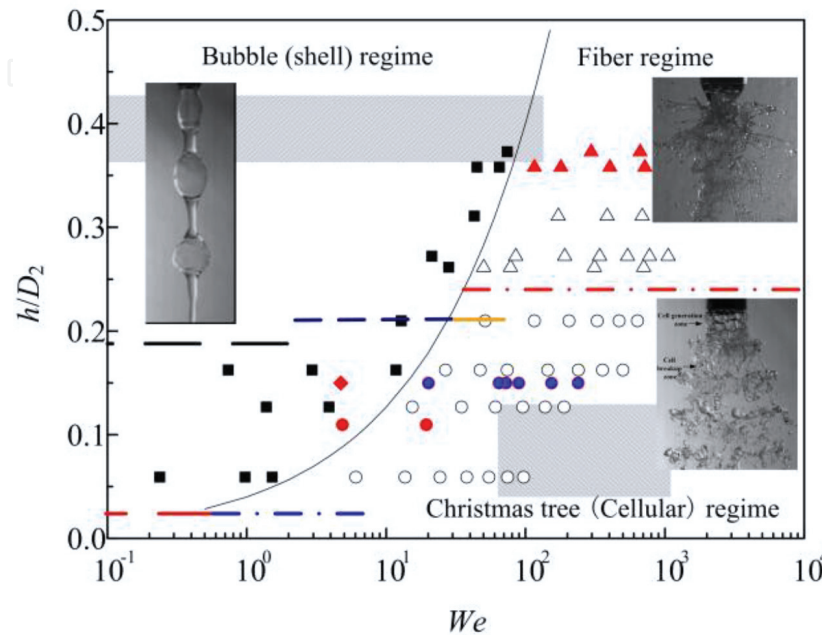


Figure 2.
Influence of h/D on atomization mode.

$We-Re_l$ map or $M-Re_g$ map is common. However, these criteria cannot reflect the impact of gas-liquid nozzle exit size. So, there is the modified map of classification by the gas-liquid nozzle exit area ratio A_g/A_l . **Figure 1** shows that atomization performance will improve with the increase of A_g/A_l , but the oversized value of A_g/A_l will produce very little effect and waste energy [41]. These results are conducive to the design of nozzles.

In cylindrical gas jet and annular liquid jet, the common atomization modes are bubble (shell) breakup, Christmas tree (cellular) breakup, fiber breakup, and so on [43–55]. Here, the characteristic size is the liquid film thickness h , which has an important impact on liquid film breakup. Then, there is the $h/D-We$ map of breakup regimes based on the Rayleigh-Taylor instability is proposed, which is in well agreement with the experimental results as shown in **Figure 2**. Note that outlet wall thickness of nozzle can affect the flow field at nozzle outlet [56–61].

4. Secondary atomization

Drop is subjected to aerodynamic forces when there is the relative velocity between drop and gas. This force results in drop deformation and, if sufficiently large, will lead to breakup and fragmentation. Differing gas flow conditions can lead to differing drop breakup modes. Based on the morphology, as We increases, the vibrational, bag, bag-stamen, multimode, sheet-thinning, shear, and catastrophic breakup mode appear in turn [62–66]. This classification method would lack the quantitative physical mechanism, which may result in the criterion of mode based primarily on subjective experience.

The mechanism of drop breakup is a key and hot research area of secondary atomization. The investigation [67] shows the structure and location of turbulent eddies, which do not appear to correlate with drop breakup morphology. The average gas flow fields show no significant differences of drop morphology between bag breakup and sheet-thinning breakup. The results show that the wake structure of gas is unlikely to be the dominant mechanism of secondary atomization. These results agree well with experimental photos that the morphological transition of drop breakup is a strong function of We , and the influence of Re_g is little [68].

Interfacial instability is very important in atomization [69, 70]. Rayleigh-Taylor (RT) instability is considered as the main driving mechanism responsible for drop breakup in the general bag breakup or Rayleigh-Taylor piercing (including bag breakup, bag-stamen breakup, dual-bag breakup, bag/plume breakup, multibag breakup, etc.) [65, 71–77]. All of these breakup modes have the same characteristic bag structure. With the increase of Weber number, the thin sheet (or membrane) at the periphery of deforming drop appears and breaks up continuously. These breakup types that have continuing shearing and entraining action are all governed by the Kelvin-Helmholtz (KH) instability mainly. This mode can be named as shear breakup (or sheet-thinning breakup, shear-induced entrainment) [65, 78]. So based on the instability in secondary atomization, there are two main modes: general bag breakup and shear breakup.

In order to classify the submode of general bag breakup, a dimensionless number of RT instability wave number is proposed [71]

$$N_{RT} = D/\lambda_{RT}, \quad (17)$$

where λ_{RT} is the wavelength of the most R-T unstable wave. N_{RT} is the number of R-T wave on the windward side, which can also be considered as the bag number

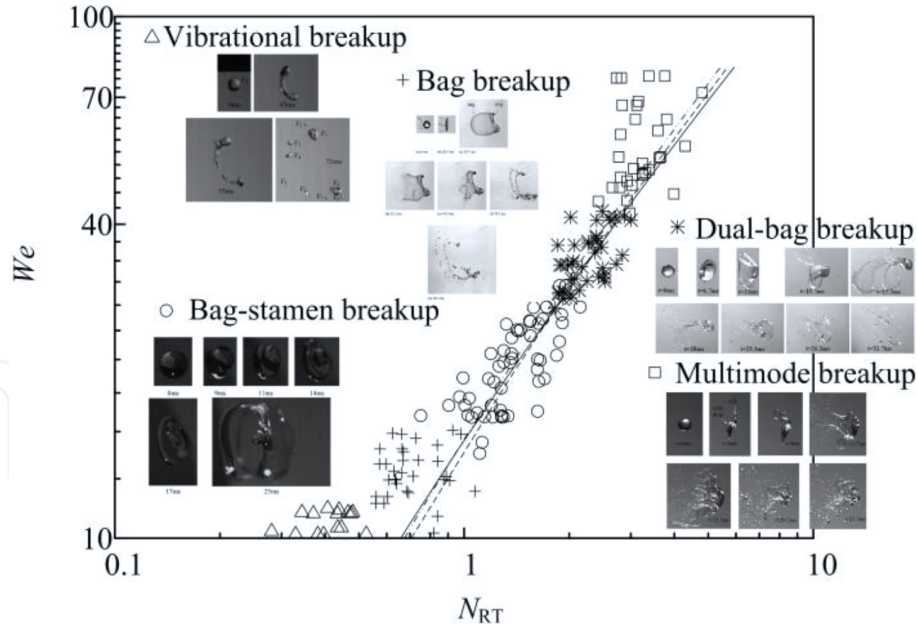


Figure 3.
Theoretical criterion N_{RT} for general bag breakup.

approximately. So the theoretical criterion N_{RT} could be the new criterion instead of We in the range of general bag breakup as shown in **Figure 3**.

When the viscosity of liquid cannot be neglected, Oh will be another key parameter [79–84]. Many researches show that the We range of drop breakup mode will increase with the increase of Oh nonlinearly. The most important transition We is the critical Weber number We_c occurring at the start of bag breakup. It can establish the criteria for the onset of secondary atomization. Based on the RT instability, the theoretical formula for predicting We_c is [81]

$$\left(\frac{We_0}{We_c}\right)^{1/2} + C\left(\frac{Oh^2}{We_c}\right)^{1/3} = 1, \quad (18)$$

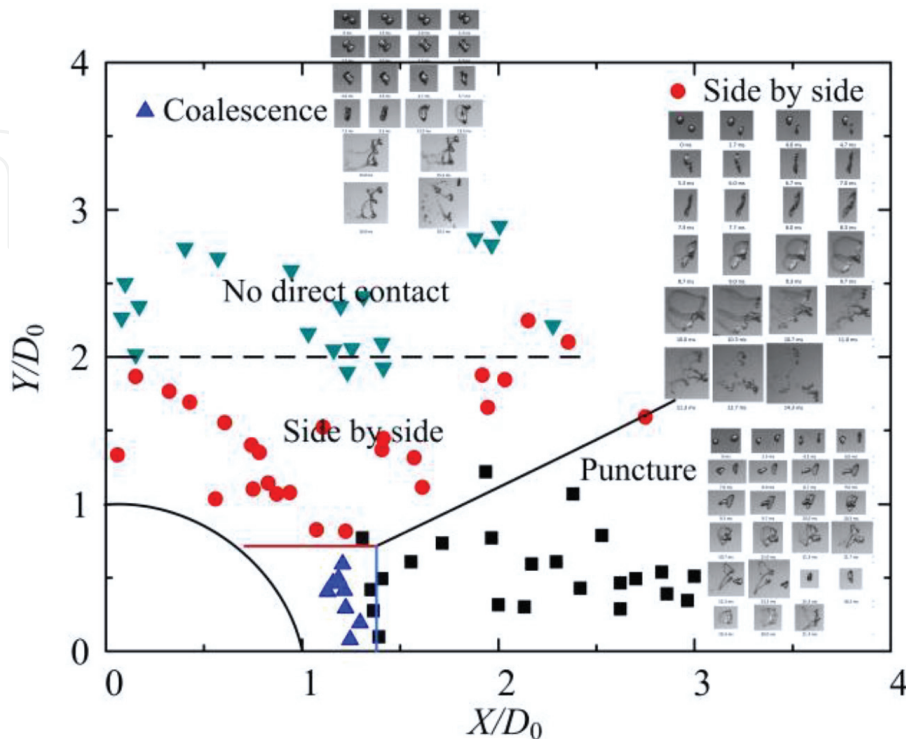


Figure 4.
Drop interaction regime map.

where We_0 is the critical Weber number when Ohnesorge number tends to zero, $We_0 = 11 \pm 2$, and C can be considered as a constant 1.48.

Drop interaction in the continuous gas jet is the important atomization process between primary atomization and secondary atomization [85]. It is the important link between the jet breakup and final spray. Due to airflow, the interaction of two drops evolves in a highly interactive and variable manner. The drop interaction in the airflow yields even more rich atomization morphologies and mechanisms. Behaviors of drop group and the isolated drop in the airflow are significantly different. Experimental photos in **Figure 4** show that there are four main interaction modes, which are coalescence mode, puncture mode, side by side mode, and no direct contact mode [86].

5. Fragment size and distribution

Drop size in atomization is a key parameter that is needed for a lot of fundamental researches and applications [87]. Due to the complicated nature of atomization, most nozzles cannot produce sprays of uniform droplet size. Instead, the spray can be regarded as a spectrum of drop sizes distributed about some defined mean drop size. Now, the most widely used mean diameter is Sauter mean diameter,

$$D_{32} \text{ or } SMD = \frac{\sum n_i d_i^3}{\sum n_i d_i^2} \quad (19)$$

where n_i is the number of droplets per unit volume in size class i , and d_i is the droplet diameter [7, 88–91].

The liquid in prefilming air-blast nozzle is first spread into a very thin sheet or film, which is then exposed to gas operating at the high velocity causing breakup and atomization. By spreading bulk liquid into film, contact area between liquid and gas increases. Generally speaking, SMD will decrease with the increase of gas velocity. However, under some conditions of prefilming atomization, the droplet size increases with the increase of gas velocity, and then decreases with the increase of gas velocity. So, the classical KH-RT atomization model [92–94] is modified and extended to the prefilming air-blast atomization [95].

Droplet size distribution is a crucial parameter of atomization process besides droplet mean diameter. Atomization and spray presents a wide distribution of fragment sizes. Many empirical relationships have been proposed to characterize the distribution of droplet sizes in atomization, for example, Rosin-Rammler, Nukiyama-Tanasawa, log-normal, root-normal, and log-hyperbolic. Atomization process involves a succession of changes of liquid topology, the last being the elongation and capillary breakup of ligaments torn off from the liquid surface. Breakup of liquid ligament (filament or fiber) is the key in primary atomization and secondary atomization, so ligament-mediated spray formation model is proposed [96, 97]. Drop fragments after ligament breakup is found to be gamma distribution. Then, the broad statistics of atomization shows Marshall-Palmer exponential shape of overall distribution in spray [98–101].

6. Complex fluids

Complex fluids are mixtures that have a coexistence between two or multiphases, which are common in our society and industry [102–104]. Many complex fluids are non-Newtonian fluid, whose characteristics of breakup and atomization are unusual [82, 105–107].

The particle concentration in the pinch-off zone of suspension or slurry decreases as its minimal diameter decreases, resulting in a pure liquid interstitial fluid. There are three successive stages during suspension pinch-off, referred to as suspension, transition, and liquid stages, which is different from pure liquids [108–111].

For evaluating the breakup of non-Newtonian fluid, the mean apparent viscosity of liquid during deformation and breakage is the key parameter. Three methods for determining the apparent viscosity of non-Newtonian fluid have been presented: (1) calculation of mean apparent viscosity according to the shear rate equal to $\gamma = u_g/D$ [112], (2) increase the constant k determined by other test parameters, $\gamma = ku_g/D$ [17, 113], and (3) numerical analysis or analytical solution of energy and motion equations to determine dynamic shear rate [114–117].

Based on morphology, the breakup regimes of slurry jet can be classified into different modes: Rayleigh-type breakup, fiber-type breakup, superpulsating breakup, and atomization [113, 118, 119]. The particles in slurry will make membrane breakup very fast, so the membrane structure is not obvious in slurry atomization as shown in **Figure 5**. The dimensionless slurry jet breakup length can be correlated by the KH-RT hybrid model [92, 93, 113, 120]. There are two kinds of periodic structures, which are shear wave and jet oscillation. The deformation and breakup regimes of slurry drops can be classified into different modes: deformation, multimode breakup (including two submodes: hole breakup and tensile breakup), and shear breakup [17, 117].

Atomization of solution is a common phenomenon in numerous practical applications [121–124]. In the breakup of surfactant-laden liquid, critical micelle concentration (CMC) has an important influence [125–129]. The micelle can be considered as the source term, which can supply the monomers [130]. The diffusion rate of surfactant is limited, and liquid breakup is very fast sometimes. So, dynamic surface tension will change with the process of liquid deformation and atomization. According to the competition of the amplification rate of KH instability ω_{km} and RT instability ω_{Rm} , the criterion on transition Weber number between general bag breakup and shear breakup is obtained [131],

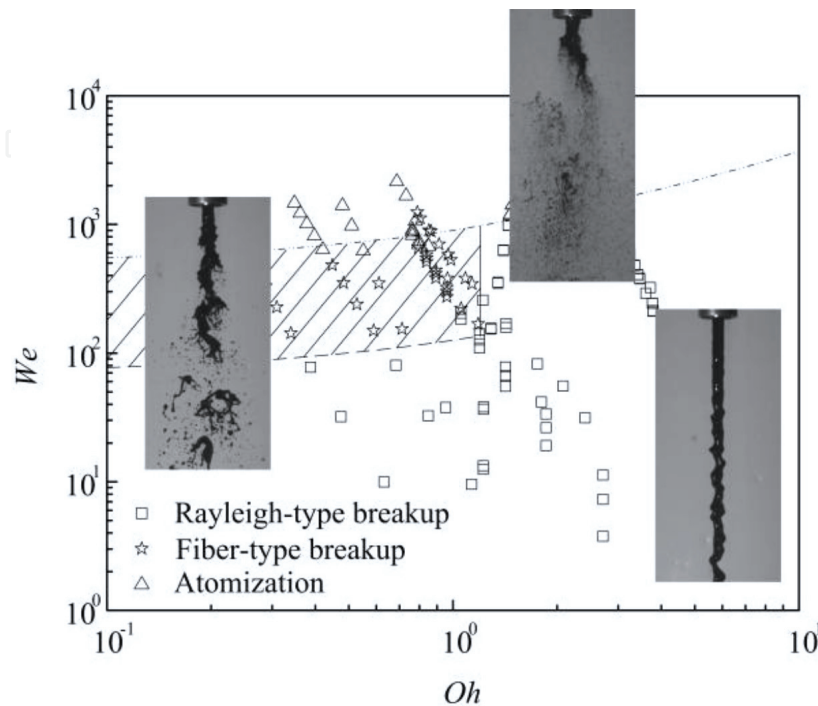


Figure 5.
The breakup regimes of slurry jet.

$$\omega_{km}/\omega_{Rm} = 1. \quad (20)$$

Atomization of viscoelastic liquids is widely known to be more difficult to atomize than typical Newtonian liquids [18, 132–138]. The addition of viscoelasticity is found to stabilize the rim of liquid. Viscoelasticity can enhance the growth of the bead and delay pinch off. Viscoelasticity increases the mean drop diameter and broadens the size distribution. Liquids with atypical properties, such as gels, liquid metal, and strain-thickening liquids, are also studied widely [139–147].

7. Conclusions

The available literature on liquid atomization is countless. Many researchers and engineers have done a lot of excellent work in this field. Unfortunately, the clear physical mechanisms on atomization have not yet been fully revealed. Some topics have received only cursory attention, such as non-Newtonian liquids, charged liquids, and turbulence influence. There are many challenges ahead for research in atomization and spray technology [148, 149]. On the other hand, it is lucky for us. Due to the fundamental nature of the problem and its many important applications, we can expect great progress in the fields of atomization and spray technology in the future.

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Conflict of interest

The authors have declared that no conflict of interest exists.


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References

- [1] Eggers J, Villermaux E. Physics of liquid jets. *Reports on Progress in Physics*. 2008;**71**(3):036601. DOI: 10.1088/0034-4885/71/3/036601
- [2] Villermaux E. Fragmentation. *Annual Review of Fluid Mechanics*. 2007;**39**(1):419-446. DOI: 10.1146/annurev.fluid.39.050905.110214
- [3] Gorokhovski M, Herrmann M. Modeling primary atomization. *Annual Review of Fluid Mechanics*. 2008;**40**(1): 343-366. DOI: 10.1146/annurev.fluid.40.111406.102200
- [4] Theofanous TG. Aerobreakup of Newtonian and viscoelastic liquids. *Annual Review of Fluid Mechanics*. 2011;**43**(1):661-690. DOI: 10.1146/annurev-fluid-122109-160638
- [5] Guildenbecher DR, López-Rivera C, Sojka PE. Secondary atomization. *Experiments in Fluids*. 2009;**46** (3):371. DOI: 10.1007/s00348-008-0593-2
- [6] Dumouchel C. On the experimental investigation on primary atomization of liquid streams. *Experiments in Fluids*. 2008;**45**(3):371-422. DOI: 10.1007/s00348-008-0526-0
- [7] Suh HK, Chang SL. A review on atomization and exhaust emissions of a biodiesel-fueled compression ignition engine. *Renewable & Sustainable Energy Reviews*. 2016;**58**:1601-1620. DOI: 10.1016/j.rser.2015.12.329
- [8] Qian L, Lin J. Modeling on effervescent atomization: A review. *Science China - Physics Mechanics & Astronomy*. 2011;**54**(12):2109-2129. DOI: 10.1007/s11433-011-4536-1
- [9] Boggavarapu P, Ravikrishna RV. A review on atomization and sprays of biofuels for IC engine applications. *International Journal of Spray and Combustion Dynamics*. 2013;**5**(2): 85-122. DOI: 10.1260/1756-8277.5.2.85
- [10] Basaran OA, Gao H, Bhat PP. Nonstandard inkjets. *Annual Review of Fluid Mechanics*. 2013;**45**:85-113. DOI: 10.1146/annurev-fluid-120710-101148
- [11] Basu S, Agarwal AK, Mukhopadhyay A, Patel C. *Droplets and Sprays, Applications for Combustion and Propulsion*. Singapore: Springer; 2018. 430p. DOI: 10.1007/978-981-10-7449-3
- [12] Sazhin S. *Droplets and Sprays*. London: Springer; 2014. 345p. DOI: 10.1007/978-981-10-7449-3
- [13] Ashgriz N. *Handbook of Atomization and Sprays*. New York: Springer; 2011. 935p. DOI: 10.1007/978-1-4419-7264-4
- [14] Lefebvre AH, McDonell VG. *Atomization and Sprays*, Second Edition. Boca Raton: CRC Press; 2017. 284p. ISBN: 9781498736268
- [15] Nasr GG, Yule AJ, Bendig L. *Industrial Sprays and Atomization Design, Analysis and Applications*. Berlin: Springer; 2002. 501p. DOI: 10.1007/978-1-4471-3816-7
- [16] Nicholls JA, Ranger AA. Aerodynamic shattering of liquid drops. *AIAA Journal*. 1968;**7**(2):285-290. DOI: 10.2514/6.1968-83
- [17] Zhao H, Liu HF, Xu JL, Li WF. Secondary breakup of coal water slurry drops. *Physics of Fluids*. 2011;**23**(11): 074501. DOI: 10.1063/1.3659495
- [18] Zhao H, Hou YB, Liu HF, Tian XS, Xu JL, Li WF, et al. Influence of rheological properties on air-blast atomization of coal water slurry. *Journal of Non-Newtonian Fluid Mechanics*.

2014;**211**:1-15. DOI: 10.1016/j.jnnfm.2014.06.007

[19] Zhong W, He Z, Wang Q, Shao Z, Tao X. Experimental study of flow regime characteristics in diesel multi-hole nozzles with different structures and enlarged scales. *International Communications in Heat and Mass Transfer*. 2014;**59**:1-10. DOI: 10.1016/j.icheatmasstransfer.2014.10.001

[20] Lahane S, Subramanian KA. Impact of nozzle holes configuration on fuel spray, wall impingement and NO_x emission of a diesel engine for biodiesel-diesel blend (B20). *Applied Thermal Engineering*. 2014;**64**(1–2):307-314. DOI: 10.1016/j.applthermaleng.2013.12.048

[21] Taghavifar H, Shervanitabar MT, Abbasalizadeh M. Numerical study of the effects of injector needle movement and the nozzle inclination angle on the internal fluid flow and spray structure of a group-hole nozzle layout. *Applied Mathematical Modelling*. 2015;**39**(23–24):7718-7733. DOI: 10.1016/j.apm.2015.04.032

[22] Xue Q, Battistoni M, Powell CF, Longman DE, Quan SP, Pomraning E, et al. An Eulerian CFD model and X-ray radiography for coupled nozzle flow and spray in internal combustion engines. *International Journal of Multiphase Flow*. 2015;**70**:77-88. DOI: 10.1016/j.ijmultiphaseflow.2014.11.012

[23] Fansler TD, Parrish SE. Spray measurement technology: A review. *Measurement Science & Technology*. 2014;**26**(1):012002. DOI: 10.1088/0957-0233/26/1/012002

[24] Gao J, Li W, Wong SP, Hu MJ, Li RKY. Controllable morphology and wettability of polymer microspheres prepared by nonsolvent assisted electrospraying. *Polymer*. 2014;**55**(12):2913-2920. DOI: 10.1016/j.polymer.2014.04.033

[25] Chandrasekhar PS, Kumar N, Swami SK, Dutta V, Komarala VK. Fabrication of perovskite films using an electrostatic assisted spray technique: The effect of the electric field on morphology, crystallinity and solar cell performance. *Nanoscale*. 2016;**8**(12):6792-6800. DOI: 10.1039/c5nr08350h

[26] Liparoti S, Adami R, Reverchon E. Supercritical assisted atomization: Effect of operative conditions on PVP microparticle size and morphology. *The Journal of Supercritical Fluids*. 2015;**97**:31-35. DOI: 10.1016/j.supflu.2014.10.028

[27] Jafari-Nodoushan M, Barzin J, Mobedi H. Size and morphology controlling of PLGA microparticles produced by electro hydrodynamic atomization. *Polymers for Advanced Technologies*. 2015;**26**(5):502-513. DOI: 10.1002/pat.3480

[28] Stunda-Zujeva A, Irbe Z, Berzina-Cimdina L. Controlling the morphology of ceramic and composite powders obtained via spray drying—A review. *Ceramics International*. 2017;**43**:11543-11551. DOI: 10.1016/j.ceramint.2017.05.023

[29] Schumaker SA, Driscoll JF. Mixing properties of coaxial jets with large velocity ratios and large inverse density ratios. *Physics of Fluids*. 2012;**24**(5):055101. DOI: 10.1063/1.4711396

[30] Jarrahbashi D, Sirignano WA, Popov PP, Hussain F. Early spray development at high gas density: Hole, ligament and bridge formations. *Journal of Fluid Mechanics*. 2016;**792**:186-231. DOI: 10.1017/jfm.2016.71

[31] Padwal MB, Jejurkar SY, Mishra DP. Experimental studies on bluff body-assisted airblast atomizer. *Atomization and Sprays*. 2016;**26**(11):1127-1150. DOI: 10.1615/AtomizSpr.2015013523

[32] Wahono S, Honnery D, Soria J, Ghajeri J. High-speed visualisation of

- primary break-up of an annular liquid sheet. *Experiments in Fluids*. 2008;**44**: 451-459. DOI: 10.1007/s00348-007-0361-8
- [33] Duke D, Honnery D, Soria J. A cross-correlation velocimetry technique for breakup of an annular liquid sheet. *Experiments in Fluids*. 2010;**49**: 435-445. DOI: 10.1007/s00348-009-0817-0
- [34] Duke D, Honnery D, Soria J. Experimental investigation of nonlinear instabilities in annular liquid sheets. *Journal of Fluid Mechanics*. 2012;**691**: 594-604. DOI: 10.1017/jfm.2011.516
- [35] Gañán-Calvo AM, Herrada MA, Garstecki P. Bubbling in unbounded coflowing liquids. *Physical Review Letters*. 2006;**96**:124504. DOI: 10.1103/PhysLettRev.96.124504
- [36] Farago Z, Chigier N. Morphological classification of disintegration of round liquid jets in a coaxial air stream. *Atomization and Sprays*. 1992;**2**:137-153. DOI: 10.1615/AtomizSpr.v2.i2.50
- [37] Lasheras JC, Villermaux E, Hopfinger EJ. Break-up and atomization of a round water jet by a high-speed annular air jet. *Journal of Fluid Mechanics*. 1998;**357**:351-379. DOI: 10.1017/S0022112097008070
- [38] Lasheras JC, Hopfinger EJ. Liquid jet instability and atomization in a coaxial gas stream. *Annual Review of Fluid Mechanics*. 2000;**32**(1):275-308. DOI: 10.1146/annurev.fluid.32.1.275
- [39] Wang Y, Im KS, Fezzaa K. Similarity between the primary and secondary air-assisted liquid jet breakup mechanisms. *Physical Review Letters*. 2008;**100**(15):154502. DOI: 10.1103/PhysRevLett.100.154502
- [40] Baillot F, Blaisot JB, Boisdron G, Dumouchel C. Behaviour of an air-assisted jet submitted to a transverse high-frequency acoustic field. *Journal of Fluid Mechanics*. 2009;**640**(640): 305-342. DOI: 10.1017/S002211200999139X
- [41] Zhao H, Liu HF, Tian XS, Xu JL, Li WF, Lin KF. Influence of atomizer exit area ratio on the breakup morphology of coaxial air and round water jets. *AIChE Journal*. 2014;**60**(6):2335-2345. DOI: 10.1002/aic.14414
- [42] Kumar A, Sahu S. Liquid jet breakup unsteadiness in a coaxial air-blast atomizer. *International Journal of Spray and Combustion Dynamics*. 2018;**10**(3): 211-230. DOI: 10.1177/1756827718760905
- [43] Kendall JM. Experiments on annular liquid jet instability and on the formation of liquid shells. *Physics of Fluids*. 1986;**29**: 2086-2094. DOI: 10.1063/1.865595
- [44] Lee JG, Chen LD. Linear stability analysis of gas-liquid interface. *AIAA Journal*. 1991;**29**(10):1589-1595. DOI: 10.2514/3.10779
- [45] Martínez-Bazán C, Montañés JL, Lasheras JC. On the breakup of an air bubble injected into a fully developed turbulent flow. Part 1. Breakup frequency. *Journal of Fluid Mechanics*. 1999;**401**:157-182. DOI: 10.1017/S0022112099006680
- [46] Martínez-Bazán C, Montañés JL, Lasheras JC. On the breakup of an air bubble injected into a fully developed turbulent flow. Part 2. Size PDF of the resulting daughter bubbles. *Journal of Fluid Mechanics*. 1999;**401**:183-207. DOI: 10.1017/S0022112099006692
- [47] Adzic M, Carvalho IS, Heitor MV. Visualisation of the disintegration of an annular liquid sheet in a coaxial airblast injector at low atomising air velocities. *Optical Diagnostics in Engineering*. 2001;**5**:27-38
- [48] Li XG, Shen JH. Experiments on annular liquid jet breakup. *Atomization*

and Sprays. 2001;**11**:557-573. DOI: 10.1615/AtomizSpr.v11.i5.50

Journal. 1994;**32**:1844-1851. DOI: 10.2514/3.12182

[49] Choi CJ, Lee SY. Droplet formation from thin hollow liquid jet with a core air flow. *Atomization and Sprays*. 2005; **15**:469-487. DOI: 10.1615/AtomizSpr.v15.i4.80

[57] Yang JT, Chang CC, Pan KL. Flow structures and mixing mechanisms behind a disc stabilizer with a central fuel jet. *Combustion Science and Technology*. 2002;**174**(3):93-124. DOI: 10.1080/00102200290021001

[50] Sevilla A, Gordillo JM, Martínez-Bazán C. Transition from bubbling to jetting in a coaxial air-water jet. *Physics of Fluids*. 2005;**17**:018105. DOI: 10.1063/1.1831312

[58] Riber E, Moureau V, García M, Poinot T, Simonin O. Evaluation of numerical strategies for large eddy simulation of particulate two-phase recirculating flows. *Journal of Computational Physics*. 2009;**228**(2): 539-564. DOI: 10.1016/j.jcp.2008.10.001

[51] Sevilla A, Gordillo JM, Martínez-Bazán C. Bubble formation in a coflowing air-water stream. *Journal of Fluid Mechanics*. 2005;**530**:181-195. DOI: 10.1017/S002211200500354X

[59] Tian XS, Zhao H, Liu HF, Li WF, Xu JL. Liquid entrainment behavior at the nozzle exit in coaxial gas-liquid jets. *Chemical Engineering Science*. 2014; **107**:93-101. DOI: 10.1016/j.ces.2013.12.008

[52] Leboucher N, Roger F, Carreau JL. Atomization characteristics of an annular liquid sheet with inner and outer gas flows. *Atomization and Sprays*. 2014;**24**(12):1065-1088. DOI: 10.1615/AtomizSpr.2014010670

[60] Tian XS, Zhao H, Liu HF, Li WF, Xu JL. Effect of central tube thickness on wave frequency of coaxial liquid jet. *Fuel Processing Technology*. 2014;**119**: 190-197. DOI: 10.1016/j.fuproc.2013.11.011

[53] Zhao H, Liu HF, Tian XS, Xu JL, Li WF, Lin KF. Outer ligament-mediated spray formation of annular liquid sheet by an inner round air stream. *Experiments in Fluids*. 2014;**55**(8): 1793-1780. DOI: 10.1007/s00348-014-1793-6

[61] Gujeong P, Jungho L, Ingyu L, Yoon Y, Hoon SC. Geometric effect on spray characteristics of gas-centered swirl coaxial injectors: Recess ratio and gap thickness. *Atomization and Sprays*. 2017;**27**(7):579-589. DOI: 10.1615/AtomizSpr.2017018958

[54] Zhao H, Xu JL, Wu JH, Li WF, Liu HF. Breakup morphology of annular liquid sheet with an inner round air stream. *Chemical Engineering Science*. 2015;**137**:412-422. DOI: 10.1016/j.ces.2015.06.062

[62] Chou WH, Hsiang LP, Faeth GM. Temporal properties of drop breakup in the shear breakup regime. *International Journal of Multiphase Flow*. 1997;**23**(4): 651-669. DOI: 10.1016/S0301-9322(97)00006-2

[55] Fu QF, Deng XD, Jia BQ, Yang LJ. Temporal instability of a confined liquid film with heat and mass transfer. *AIAA Journal*. 2018;1-8. DOI: 10.2514/1.J056834

[63] Chou WH, Faeth GM. Temporal properties of secondary drop breakup in the bag breakup regime. *International Journal of Multiphase Flow*. 1998;**24**(6): 889-912. DOI: 10.1016/S0301-9322(98)00015-9

[56] Schefer R, Namazian M, Kelly J. Velocity measurements in turbulent bluff-body stabilized flows. *AIAA*

- [64] Dai Z, Faeth GM. Temporal properties of secondary drop breakup in the multimode breakup regime. *International Journal of Multiphase Flow*. 2001;27(2):217-236. DOI: 10.1016/S0301-9322(00)00015-X
- [65] Theofanous TG, Li GJ, Dinh TN. Aerobreakup in rarefied supersonic gas flows. *Journal of Fluids Engineering*. 2004;126(4):516-527. DOI: 10.1115/1.1777234
- [66] Zhao H, Liu HF, Xu JL, Li WF, Lin KF. Temporal properties of secondary drop breakup in the bag-stamen breakup regime. *Physics of Fluids*. 2013;25(5):1741. DOI: 10.1063/1.4803154
- [67] Flock AK, Guildenbecher DRR, Chen J, Sojka PE, Bauer H-J. Experimental statistics of droplet trajectory and air flow during aerodynamic fragmentation of liquid drops. *International Journal of Multiphase Flow*. 2012;47(3):37-49. DOI: 10.1016/j.ijmultiphaseflow.2012.06.008
- [68] Lee CH, Reitz RD. An experimental study of the effect of gas density on the distortion and breakup mechanism of drops in high speed gas stream. *International Journal of Multiphase Flow*. 2000;26(2):229-244. DOI: 10.1016/S0301-9322(99)00020-8
- [69] Reitz R. Modeling atomization processes in high-pressure vaporizing sprays. *Atomization and Spray Technology*. 1987;3(4):309-337
- [70] Joseph DD, Belanger J, Beavers GS. Breakup of a liquid drop suddenly exposed to a high-speed airstream. *International Journal of Multiphase Flow*. 1999;25(6-7):1263-1303. DOI: 10.1016/S0301-9322(99)00043-9
- [71] Zhao H, Liu HF, Li WF, Xu JL. Morphological classification of low viscosity drop bag breakup in a continuous air jet stream. *Physics of Fluids*. 2010;22(11):114103. DOI: 10.1063/1.3490408
- [72] Rimbert N, Castanet G. Crossover between Rayleigh-Taylor instability and turbulent cascading atomization mechanism in the bag-breakup regime. *Physical Review. E, Statistical, Nonlinear, and Soft Matter Physics*. 2011;84(1 Pt 2):016318. DOI: 10.1103/PhysRevE.84.016318
- [73] Jalaal M, Mehravaran K. Transient growth of droplet instabilities in a stream. *Physics of Fluids*. 2014;26(1):012101. DOI: 10.1063/1.4851056
- [74] Jain M, Prakash RS, Tomar G, Ravikrishna RV. Secondary breakup of a drop at moderate Weber numbers. *Proceedings of the Royal Society of London*. 2015;471(2177):20140930. DOI: 10.1098/rspa.2014.0930
- [75] Yang W, Jia M, Che Z, Sun K, Wang TY. Transitions of deformation to bag breakup and bag to bag-stamen breakup for droplets subjected to a continuous gas flow. *International Journal of Heat and Mass Transfer*. 2017;111:884-894. DOI: 10.1016/j.ijheatmasstransfer.2017.04.012
- [76] Xiao F, Dianat M, Mcguirk JJ. A robust interface method for drop formation and breakup simulation at high density ratio using an extrapolated liquid velocity. *Computers & Fluids*. 2016;136:402-420. DOI: 10.1016/j.compfluid.2016.06.021
- [77] Xiao F, Wang ZG, Sun MB, Liu N, Yang X. Simulation of drop deformation and breakup in supersonic flow. *Proceedings of the Combustion Institute*. 2017;36(2):2417-2424. DOI: 10.1016/j.proci.2016.09.016
- [78] Theofanous TG, Li GJ. On the physics of aerobreakup. *Physics of Fluids*. 2008;20(5):052103. DOI: 10.1063/1.2907989

- [79] Hsiang LP, Faeth GM. Drop deformation and breakup due to shock wave and steady disturbances. *International Journal of Multiphase Flow*. 1994;**21**(4):545-560. DOI: 10.1016/0301-9322(94)00095-2
- [80] Zhao H, Liu HF, Cao XK, Li WF, Xu JL. Breakup characteristics of liquid drops in bag regime by a continuous and uniform air jet flow. *International Journal of Multiphase Flow*. 2011;**37**(5): 530-534. DOI: 10.1016/j.ijmultiphaseflow.2010.12.006
- [81] Theofanous TG, Mitkin VV, Ng CL, Chang C-H, Deng X, Sushchikh S. The physics of aerobreakup. II. Viscous liquids. *Physics of Fluids*. 2012;**24**(2):022104. DOI: 10.1063/1.3680867
- [82] Müller T, Sängler A, Habisreuther P, Jakobs T, Trimis D, Kolb T, et al. Simulation of the primary breakup of a high-viscosity liquid jet by a coaxial annular gas flow. *International Journal of Multiphase Flow*. 2016;**87**:212-228. DOI: 10.1016/j.ijmultiphaseflow.2016.09.008
- [83] Stefanitsis D, Malgarinos I, Strotos G, Nikolopoulos N, Kakaras E, Gavaises M. Numerical investigation of the aerodynamic breakup of diesel and heavy fuel oil droplets. *International Journal of Heat and Fluid Flow*. 2017;**68**: 203-215. DOI: 10.1016/j.ijheatfluidflow.2017.10.012
- [84] Strotos G, Malgarinos I, Nikolopoulos N, Gavaises M, Nikas KS, Moustris K. Determination of the aerodynamic droplet breakup boundaries based on a total force approach. *International Journal of Heat and Fluid Flow*. 2018;**69**:164-173. DOI: 10.1016/j.ijheatfluidflow.2018.01.001
- [85] Theofanous TG, Li GJ, Dinh TN, Chang CH. Aerobreakup in disturbed subsonic and supersonic flow fields. *Journal of Fluid Mechanics*. 2007; **593**(593):131-170. DOI: 10.1017/S0022112007008853
- [86] Zhao H, Wu ZW, Li WF, Xu JL, Liu HF. Interaction of two drops in the bag breakup regime by a continuous air jet. *Fuel*. 2019;**236**:843-850. DOI: 10.1016/j.fuel.2018.09.067
- [87] Babinsky E, Sojka PE. Modeling drop size distributions. *Progress in Energy and Combustion Science*. 2002; **28**(4):303-329. DOI: 10.1016/S0360-1285(02)00004-7
- [88] Lee S, Park S. Experimental study on spray break-up and atomization processes from GDI injector using high injection pressure up to 30MPa. *International Journal of Heat and Fluid Flow*. 2014;**45**:14-22. DOI: 10.1016/j.ijheatfluidflow.2013.11.005
- [89] Ghasemi A, Barron RM, Balachandar R. Spray-induced air motion in single and twin ultra-high injection diesel sprays. *Fuel*. 2014; **121**(2):284-297. DOI: 10.1016/j.fuel.2013.12.041
- [90] Agarwal AK, Dhar A, Gupta JG, Kim WI, Choi K, Lee CS, et al. Effect of fuel injection pressure and injection timing of Karanja biodiesel blends on fuel spray, engine performance, emissions and combustion characteristics. *Energy Conversion and Management*. 2015;**91**:302-314. DOI: 10.1016/j.enconman.2014.12.004
- [91] Mo J, Tang C, Li J, Guan L, Huang ZH. Experimental investigation on the effect of n-butanol blending on spray characteristics of soybean biodiesel in a common-rail fuel injection system. *Fuel*. 2016;**182**:391-401. DOI: 10.1016/j.fuel.2016.05.109
- [92] Varga CM, Lasheras JC, Hopfinger EJ. Initial breakup of a small-diameter liquid jet by a high-speed gas stream. *Journal of Fluid Mechanics*.

2003;**497**:405-434. DOI: 10.1017/S0022112003006724

[93] Aliseda A, Hopfinger EJ, Lasheras JC, Kremer DM, Berchielli A, Connolly EK. Atomization of viscous and non-Newtonian liquids by a coaxial, high-speed gas jet. Experiments and droplet size modeling. *International Journal of Multiphase Flow*. 2008;**34**(2):161-175. DOI: 10.1016/j.ijmultiphaseflow.2007.09.003

[94] Vadivukkarasan M, Panchagnula MV. Combined Rayleigh-Taylor and Kelvin-Helmholtz instabilities on an annular liquid sheet. *Journal of Fluid Mechanics*. 2017;**812**:152-177. DOI: 10.1017/jfm.2016.784

[95] Zhao H, Wu ZW, Li WF, Xu JL, Liu HF. Nonmonotonic effects of aerodynamic force on droplet size of prefilming air-blast atomization. *Industrial & Engineering Chemistry Research*. 2018;**57**(5):1726-1732. DOI: 10.1021/acs.iecr.7b05026

[96] Villermaux E, Marmottant P, Duplat J. Ligament-mediated spray formation. *Physical Review Letters*. 2004;**92**(7):074501. DOI: 10.1103/PhysRevLett.92.074501

[97] Marmottant P, Villermaux E. On spray formation. *Journal of Fluid Mechanics*. 2004;**498**(498):73-111. DOI: 10.1017/S0022112003006529

[98] Villermaux E, Bossa B. Single-drop fragmentation determines size distribution of raindrops. *Nature Physics*. 2009;**5**(9):697-702. DOI: 10.1038/NPHYS1340

[99] Villermaux E, Bossa B. Drop fragmentation on impact. *Journal of Fluid Mechanics*. 2011;**668**(4):412-435. DOI: 10.1017/S002211201000474X

[100] Zhao H, Liu HF, Xu JL, Li WF. Experimental study of drop size distribution in the bag breakup regime.

Industrial & Engineering Chemistry Research. 2011;**50**(16):9767-9773. DOI: 10.1021/ie200622d

[101] Stefan K, Rick S, Denn MM, Villermaux E, Bonn D. What determines the drop size in sprays. *Physical Review X*. 2018;**8**(3):031019. DOI: 10.1103/PhysRevX.8.031019

[102] Divoux T, Fardin MA, Manneville S, Lerouge S. Shear banding of complex fluids. *Annual Review of Fluid Mechanics*. 2015;**48**(48):81-103. DOI: 10.1146/annurev-fluid-122414-034416

[103] Waigh TA. Advances in the microrheology of complex fluids. *Reports on Progress in Physics*. 2016;**79**(7):074601. DOI: 10.1088/0034-4885/79/7/074601

[104] Patteson AE, Gopinath A, Arratia PE. Active colloids in complex fluids. *Current Opinion in Colloid & Interface Science*. 2016;**21**:86-96. DOI: 10.1016/j.cocis.2016.01.001

[105] Keshavarz B, Sharma V, Houze EC, Koerner MR, Moore JR, Cotts PM, et al. Studying the effects of elongational properties on atomization of weakly viscoelastic solutions using Rayleigh Ohnesorge Jetting Extensional Rheometry (ROJER). *Journal of Non-Newtonian Fluid Mechanics*. 2015;**222**:171-189. DOI: 10.1016/j.jnnfm.2014.11.004

[106] Broniarz-Press L, Sosnowski TR, Matuszak M, Ochowiak M, Jablczynska K. The effect of shear and extensional viscosities on atomization of Newtonian and non-Newtonian fluids in ultrasonic inhaler. *International Journal of Pharmaceutics*. 2015;**485**(1-2):41-49. DOI: 10.1016/j.ijpharm.2015.02.065

[107] Bienia M, Lejeune M, Chambon M, Baco-Carles V, Dossou-Yovo C, Noguera R, et al. Inkjet printing of ceramic colloidal suspensions: Filament growth and breakup. *Chemical*

Engineering Science. 2016;**149**:1-13.
 DOI: 10.1016/j.ces.2016.04.015

[108] Zhao H, Liu HF, Xu JL, Li WF, Lin KF. Inhomogeneity in breakup of suspensions. *Physics of Fluids*. 2015; **27**(6):419. DOI: 10.1063/1.4922582

[109] Mathues W, Mcilroy C, Harlen OG, Clasen C. Capillary breakup of suspensions near pinch-off. *Physics of Fluids*. 2015;**27**(9):093301. DOI: 10.1063/1.4930011

[110] Zou J, Lin F, Ji C. Capillary breakup of armored liquid filaments. *Physics of Fluids*. 2017;**29**(6):062103. DOI: 10.1063/1.4984836

[111] Mariano RR, Wouter M, Alejandro S, Clasen C. One-dimensional modelling of the thinning of particulate suspensions near pinch-off. *International Journal of Multiphase Flow*. 2018;**108**:202-210. DOI: 10.1016/j.ijmultiphaseflow.2018.06.007

[112] Lopez-Rivera C, Sojka PE. Secondary breakup of non-Newtonian liquid drops. In: ILASS Europ. 22nd European Conference on Liquid Atomization and Spray Systems. Como Lake, Italy; 2008

[113] Zhao H, Liu HF, Xu JL, Li WF, Cheng W. Breakup and atomization of a round coal water slurry jet by an annular air jet. *Chemical Engineering Science*. 2012;**78**:63-74. DOI: 10.1016/j.ces.2012.05.007

[114] Dechelette A, Sojka PE, Wassgren CR. Non-Newtonian drops spreading on a flat surface. *Journal of Fluids Engineering*. 2010;**132**(10):101302. DOI: 10.1115/1.4002281

[115] An SM, Lee SY. One-dimensional model for the prediction of impact dynamics of a shear-thinning liquid drop on dry solid surfaces. *Atomization and Sprays*. 2012;**22**(5):371-389. DOI: 10.1615/AtomizSpr.2012005599

[116] Focke C, Bothe D. Direct numerical simulation of binary off-center collisions of shear thinning droplets at high Weber numbers. *Physics of Fluids*. 2012;**24**(7):073105. DOI: 10.1063/1.4737582

[117] Tavangar S, Hashemabadi SH, Saberimoghadam A. CFD simulation for secondary breakup of coal-water slurry drops using OpenFOAM. *Fuel Processing Technology*. 2015;**132**:153-163. DOI: 10.1016/j.fuproc.2014.12.037

[118] Wayne S, Francine B. The effects of pulsation and retraction on non-Newtonian flows in three-stream injector atomization systems. *Chemical Engineering Journal*. 2017; **309**(1):532-544. DOI: 10.1016/j.cej.2016.10.046

[119] Jampolski L, Sanger A, Jakobs T, Guthausen G, Kolb T, Willenbacher N. Improving the processability of coke water slurries for entrained flow gasification. *Fuel*. 2016;**185**:102-111. DOI: 10.1016/j.fuel.2016.07.102

[120] Beale JC, Reitz RD. Modeling spray atomization with the Kelvin-Helmholtz/Rayleigh-Taylor hybrid model. *Atomization and Sprays*. 1999; **9**(6):623-650. DOI: 10.1615/AtomizSpr.v9.i6.40

[121] Broniarz-Press L, Ochowiak M, Woziwodzki S. Atomization of PEO aqueous solutions in effervescent atomizers. *International Journal of Heat and Fluid Flow*. 2010;**31**(4):651-658. DOI: 10.1016/j.ijheatfluidflow.2010.02.005

[122] Stabile L, Trassiera CV, Dell'Agli G, Buonanno G. Ultrafine particle generation through atomization technique: The influence of the solution. *Aerosol and Air Quality Research*. 2013; **13**(6):1667-1677. DOI: 10.4209/aaqr.2013.03.0085

- [123] Husain O, Lau W, Edirisinghe M, Parhizkar M. Investigating the particle to fibre transition threshold during electrohydrodynamic atomization of a polymer solution. *Materials Science and Engineering C*. 2016;**65**:240-250. DOI: 10.1016/j.msec.2016.03.076
- [124] Zhao H, Zhang WB, Xu JL, Li WF, Liu HF. Surfactant-laden drop jellyfish-breakup mode induced by the Marangoni effect. *Experiments in Fluids*. 2017;**58**(3):13. DOI: 10.1007/s00348-016-2296-4
- [125] Edmonstone BD, Craster RV, Matar OK. Surfactant-induced fingering phenomena beyond the critical micelle concentration. *Journal of Fluid Mechanics*. 2006;**564**:105-138. DOI: 10.1017/S0022112006001352
- [126] Rother MA, Davis RH. Buoyancy-driven breakup of an isolated drop with surfactant. *Physical Review Letters*. 2008;**101**(4):044501. DOI: 10.1103/PhysRevLett.101.044501
- [127] Roché M, Aytouna M, Bonn D, Kellay H. Effect of surface tension variations on the pinch-off behavior of small fluid drops in the presence of surfactants. *Physical Review Letters*. 2009;**103**(26):264501. DOI: 10.1103/PhysRevLett.103.264501
- [128] de Saint Vincent MR, Petit J, Aytouna M, Delville JP, Bonn D, Kelly H. Dynamic interfacial tension effects in the rupture of liquid necks. *Journal of Fluid Mechanics*. 2012;**692**:499-510. DOI: 10.1017/jfm.2011.550
- [129] Karapetsas G, Bontozoglou V. The primary instability of falling films in the presence of soluble surfactants. *Journal of Fluid Mechanics*. 2013;**729**:123-150. DOI: 10.1017/jfm.2013.291
- [130] Zhao H, Zhang WB, Xu JL, Li WF, Liu HF. Influence of surfactant on the drop bag breakup in a continuous air jet stream. *Physics of Fluids*. 2016;**28**(5):054102. DOI: 10.1063/1.4947575
- [131] Zhao H, Wu ZW, Li WF, Xu JL, Liu HF. Transition Weber number between surfactant-laden drop bag breakup and shear breakup of secondary atomization. *Fuel*. 2018;**221**:138-143. DOI: 10.1016/j.fuel.2018.02.119
- [132] Christanti Y, Walker LM. Quantifying air atomization of viscoelastic fluids through fluid relaxation times. *Atomization and Sprays*. 2006;**16**(7):777-790. DOI: 10.1615/AtomizSpr.v16.i7.50
- [133] Thompson JC, Rothstein JP. The atomization of viscoelastic fluids in flat-fan and hollow-cone spray nozzles. *Journal of Non-Newtonian Fluid Mechanics*. 2007;**147**(1-2):11-22. DOI: 10.1016/j.jnnfm.2007.06.004
- [134] Bhat PP, Appathurai S, Harris MT, Pasquali M, McKinley GH, Basaran OA. Formation of beads-on-a-string structures during break-up of viscoelastic filaments. *Nature Physics*. 2010;**6**(8):625-631. DOI: 10.1038/NPHYS1682
- [135] Li L, Green SI, Davy MH, Eadie DT. Viscoelastic air-blast sprays in a cross-flow. Part 1: Penetration and dispersion. *Atomization and Sprays*. 2010;**20**(8):697-720. DOI: 10.1615/AtomizSpr.v20.i8.30
- [136] Li L, Green SI, Davy MH, Eadie DT. Viscoelastic air-blast sprays in a cross-flow. Part 2: Droplet velocities. *Atomization and Sprays*. 2010;**20**(8):721-735. DOI: 10.1615/AtomizSpr.v20.i8.40
- [137] Ruo AC, Chen F, Chung CA, Chang MH. Three-dimensional response of unrelaxed tension to instability of viscoelastic jets. *Journal of Fluid Mechanics*. 2011;**1**:1-19. DOI: 10.1017/jfm.2011.255

- [138] Theofanous TG, Mitkin VV, Ng CL. The physics of aerobreakup. III. Viscoelastic liquids. *Physics of Fluids*. 2013;**25**(3):032101. DOI: 10.1063/1.4792712
- [139] Padwal MB, Mishra DP. Interactions among synthesis, rheology, and atomization of a gelled propellant. *Rheologica Acta*. 2016;**55**(3):177-186. DOI: 10.1007/s00397-015-0903-6
- [140] Kim H, Ko T, Kim S, Yoon W. Spray characteristics of aluminized-gel fuels sprayed using pressure-swirl atomizer. *Journal of Non-Newtonian Fluid Mechanics*. 2017;**249**:36-47. DOI: 10.1016/j.jrinfm.2017.08.003
- [141] Jejurkar SY, Yadav G, Mishra DP. Visualizations of sheet breakup of non-Newtonian gels loaded with nanoparticles. *International Journal of Multiphase Flow*. 2018;**100**:57-76. DOI: 10.1016/j.ijmultiphaseflow.2017.12.003
- [142] Mates SP, Settles GS. A study of liquid metal atomization using close-coupled nozzles, Part 1: Gas dynamic behavior. *Atomization and Sprays*. 2005;**15**(1):19-40. DOI: 10.1615/AtomizSpr.v15.i1.20
- [143] Mates SP, Settles GS. A study of liquid metal atomization using close-coupled nozzles, part 2: Atomization behavior. *Atomization and Sprays*. 2005;**15**(1):41-60. DOI: 10.1615/AtomizSpr.v15.i1.30
- [144] Lin M, Zhong M, Li Y, Yuan M, Yang Y. Numerical analysis on molten droplet hydrodynamic deformation and surface waves under high pressure pulse. *Annals of Nuclear Energy*. 2015;**77**:133-141. DOI: 10.1016/j.anucene.2014.11.008
- [145] Manickam L, Bechta S, Ma W. On the fragmentation characteristics of melt jets quenched in water. *International Journal of Multiphase Flow*. 2017;**91**:262-275. DOI: 10.1016/j.ijmultiphaseflow.2017.02.005
- [146] Yi C, Wagner JL, Farias PA, DeMauro EP, Guildenbecher DR. Galinstan liquid metal breakup and droplet formation in a shock-induced cross-flow. *International Journal of Multiphase Flow*. 2018;**106**:147-163. DOI: 10.1016/j.ijmultiphaseflow.2018.05.015
- [147] Mitkin VV, Theofanous TG. The physics of aerobreakup. IV. Strain-thickening liquids. *Physics of Fluids*. 2017;**29**(12):122101. DOI: 10.1063/1.4997009
- [148] Chigier N. Challenges for future research in atomization and spray technology: Arthur Lefebvre memorial lecture. *Atomization and Sprays*. 2006;**16**(7):727-736. DOI: 10.1615/AtomizSpr.v16.i7.10
- [149] Jiang X, Siamas GA, Jagus K, Karayiannis TG. Physical modelling and advanced simulations of gas-liquid two-phase jet flows in atomization and sprays. *Progress in Energy and Combustion Science*. 2010;**36**(2):131-167. DOI: 10.1016/j.pecs.2009.09.002